Agent-based Modeling Approaches for Simulating Infectious Diseases

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SAMSI Program on Computational Methods in Social Sciences

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Motivation

"Previously, scientists had two pillars of understanding: theory and experiment. Now there is a third pillar: **simulation**"

U.S. Secretary of Energy **Steven Chu**"

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Agent-based Model (ABM)

A computational approach for simulating the actions of agents that interact within an environment.

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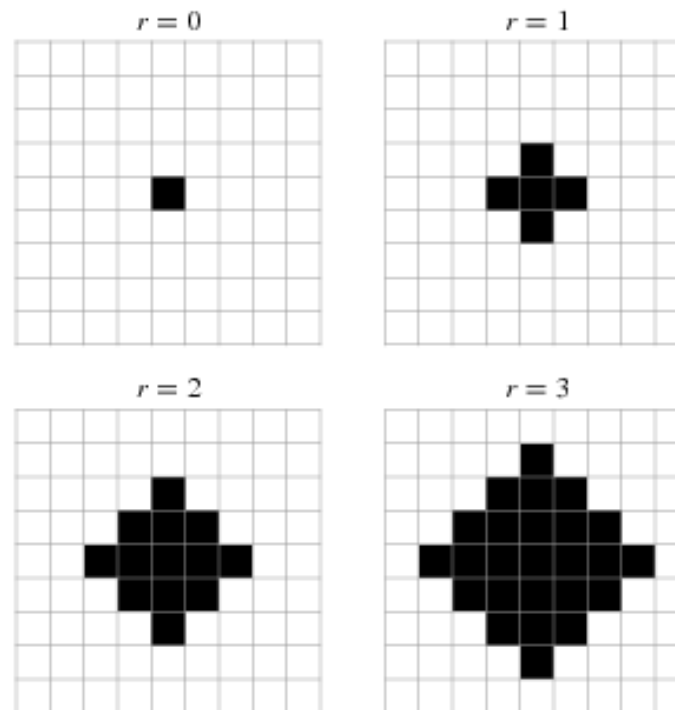Institutes of Health

NNSA

Agent-based Model (ABM)

A computational approach for simulating the actions of agents that interact within an environment.
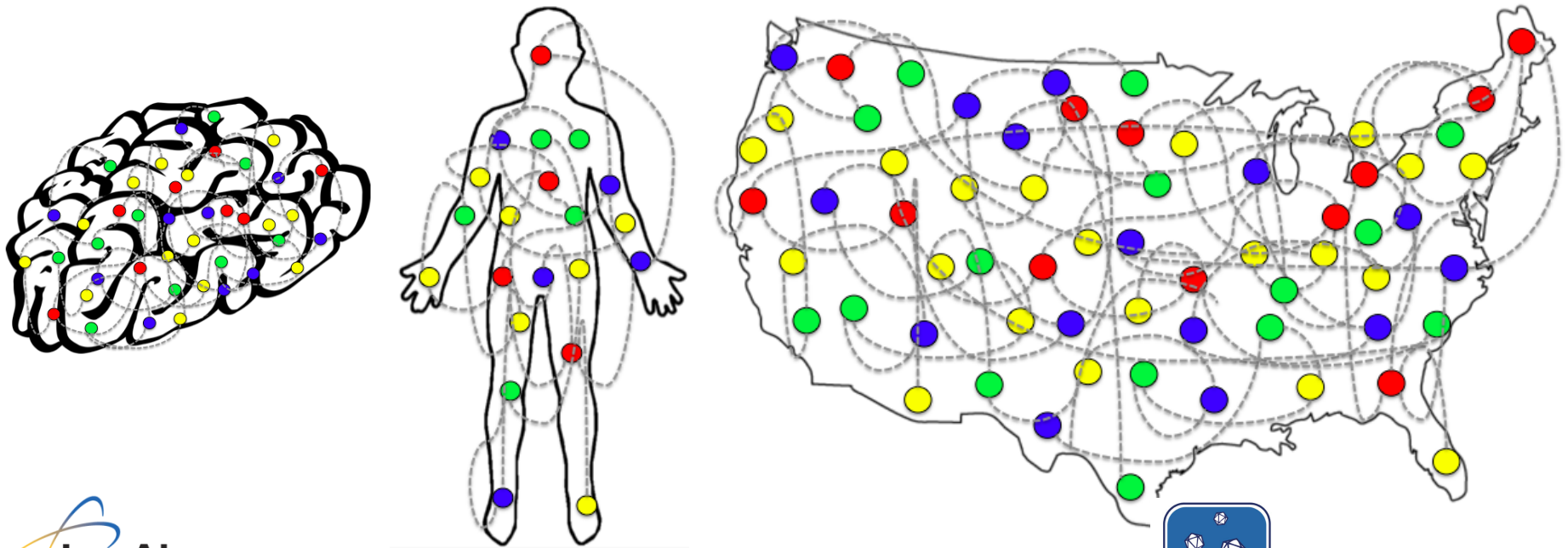
ABM History

- The concept was originally discovered in the 1940s by Stanislaw **Ulam** and John **von Neumann** while working at LANL

Von Neumann Neighborhood

ABM History

- Due to the computational requirements, ABMs did not become widespread until the 1990s

SimCity

Why ABM?

- System is too complex to be captured by analytical expressions or experiments

- Experiments are too expensive or undesirable

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ABM Characteristics

- Heterogeneity

- Individual Agent Behavior Specification

- Explicit Space

- Complex Interactions

- Randomness

- Emergent Phenomena

Ecological Systems

"…and the thousands of fishes moved as a huge beast, piercing the water. They appeared united, inexorably bound to a common fate. How comes this unity?"

-- Anonymous, 17th century

Ecological Systems

- Understand the causes of this behavior

- Fish, ants, humans, locus, birds, honeybees, immune system, bacterial infection, tumor proliferation

- Locus plagues can contain up to 10^9 individuals

Ecological Systems

- ## Experiments
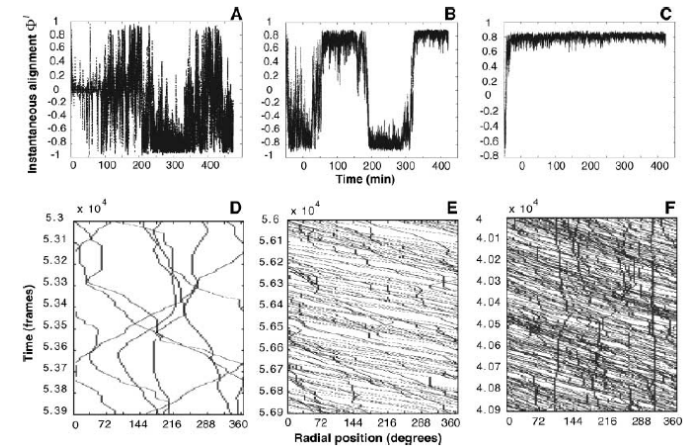
- ## Theory

$$\theta_n(t + \Delta t) = \text{Angle}[\vec{U}_n(t)] + \eta\xi_n(t),$$

$$\vec{v}_n(t + \Delta t) = v e^{i\theta_n(t+\Delta t)},$$

$$\vec{x}_n(t + \Delta t) = \vec{x}_n(t) + \vec{v}_n(t + \Delta t)\Delta t,$$
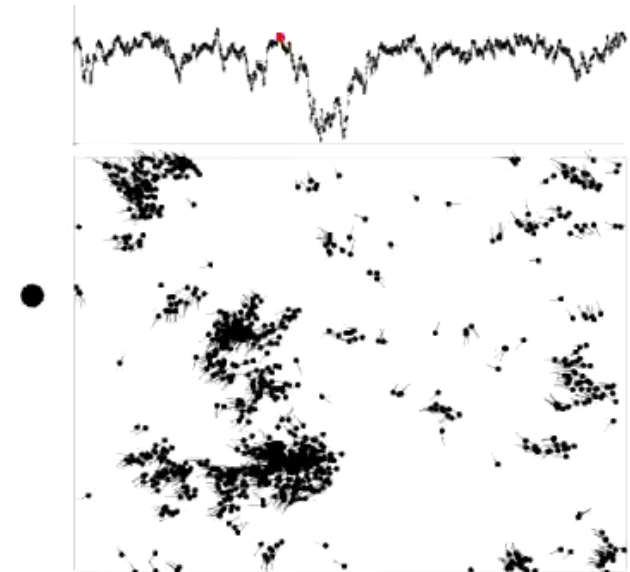
- ## Simulation

Transportation Systems

CNN World

Epic traffic jam in China leaves drivers stuck for 9 days

By the CNN Wire Staff
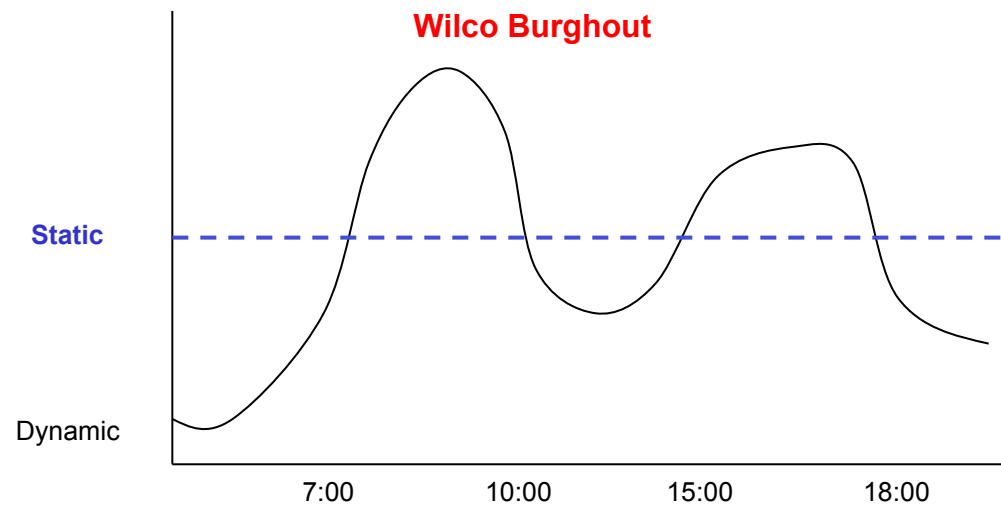August 23, 2010 11:18 a.m. EDT

Transportation Systems

- ## Experiments

Leonardi S.

- ## Theory

Wilco Burghout

Static

Dynamic

7:00   10:00   15:00   18:00

Transportation Systems - TRANSIMS

Epidemiological Studies

15,000,000

People die every year from infectious diseases

Global Disease Burden

Asthma and chronic obstructive pulmonary disease
3.0 million

All other causes of death
10.1 million

Cardiovascular conditions
16.7 million

Injuries
5.2 million

Neoplastic diseases
7.1 million

Infectious diseases
14.9 million
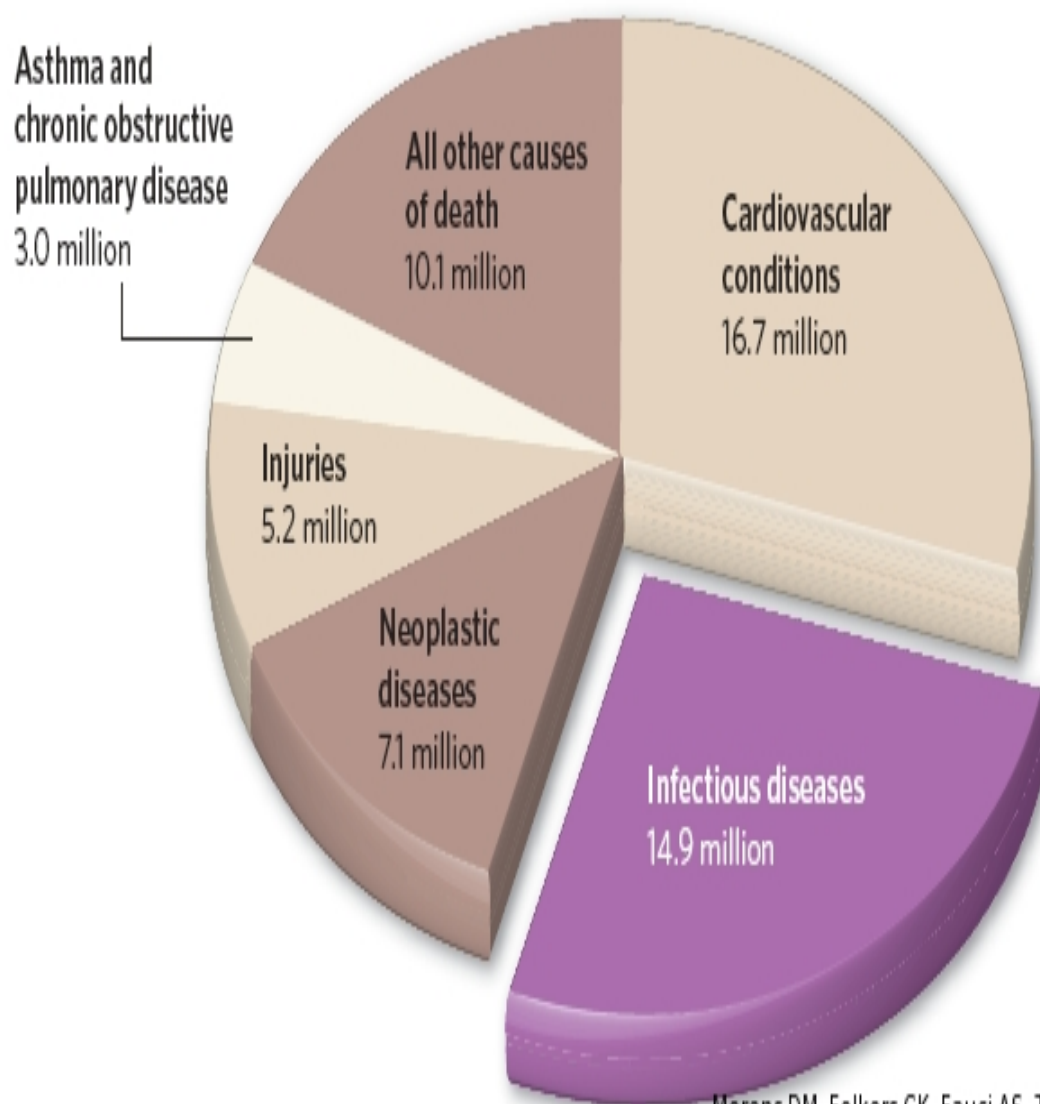
Infectious diseases	Annual deaths (millions)
Respiratory infections	3.96
HIV/AIDS	2.77
Diarrhoeal diseases	1.80
Tuberculosis	1.56
Vaccine-preventable childhood diseases	1.12
Malaria	1.27
STDs (other than HIV)	0.18
Meningitis	0.17
Hepatitis B and C	0.16
Tropical parasitic diseases	0.13
Dengue	0.02
Other infectious diseases	1.76

Morens DM, Folkers GK, Fauci AS. The challenge of emerging and re-emerging infectious diseases. Nature 2004;430:242-249.

Disease Agent Study
Funded by the National Institutes of Health

MALARIA

Source: http://en.wikipedia.org/wiki/Image:Anopheles_stephensi.jpeg {{PD-USGov-HHS-CDC}}

DIARRHEAL DISEASES

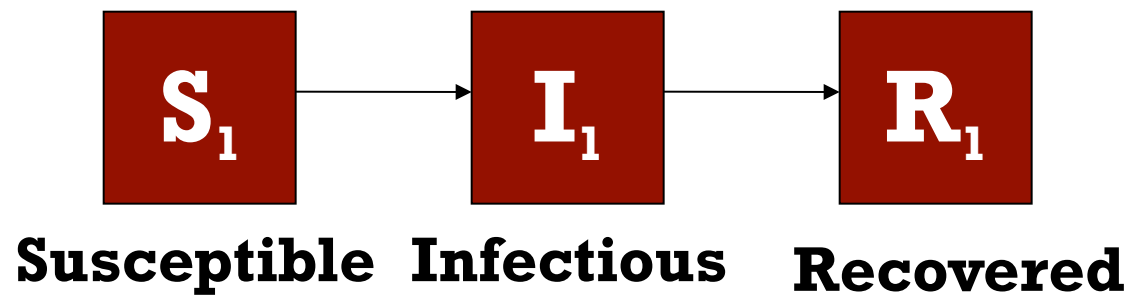RESPIRATORY INFECTIONS

RESPIRATORY INFECTIONS

Epidemic Modeling

- Experiments

- Theory

Epicurve from March 1, 2013

S_1 → I_1 → R_1

Susceptible Infectious Recovered
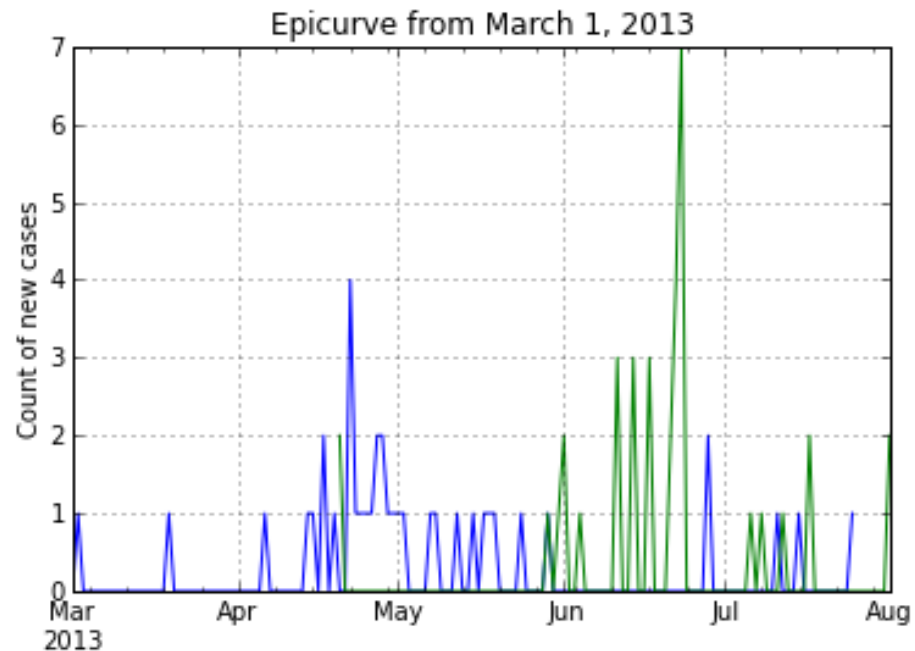
Agent-based Model (ABM)

- **Empirical Studies**

  - National Household Transportation Survey

  - Workgroup size by industry classification

  - Student-teacher ratio

  - U.S. Census Data

- **Theoretical Studies**

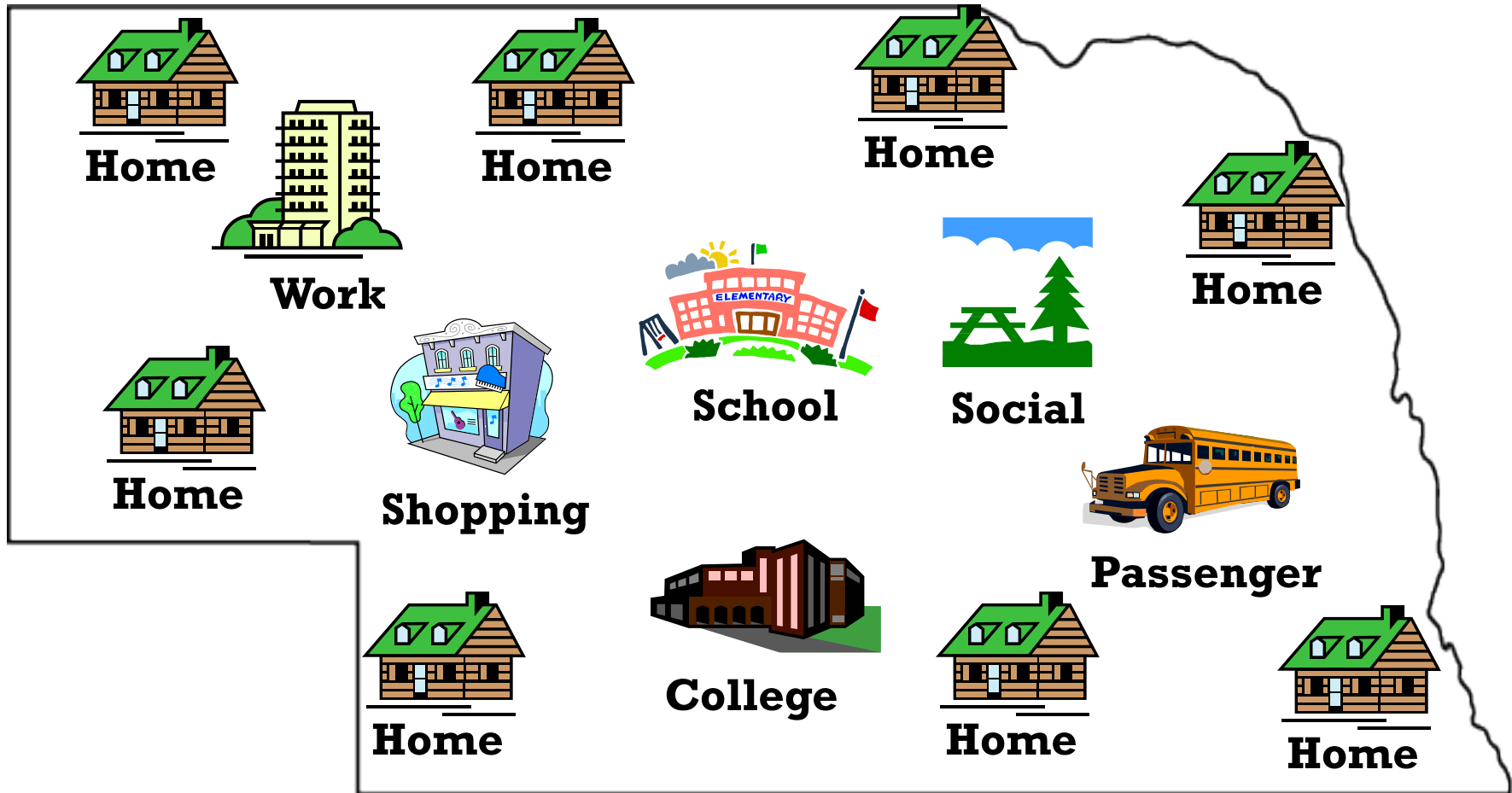 - Gravity algorithms

  - Monte Carlo methods
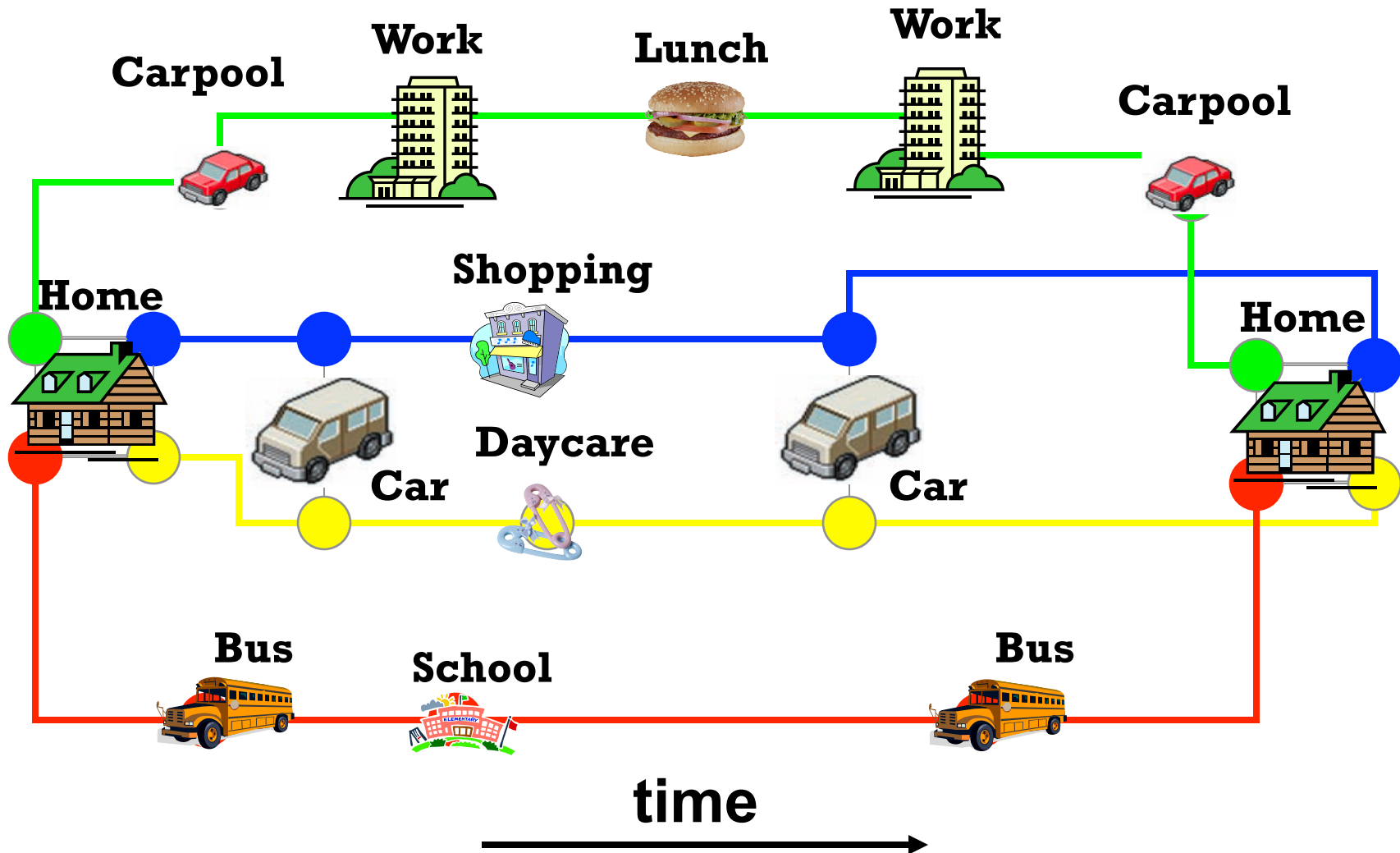
The Demographics – Surveys

HOUSEHOLD #2375

Age:	28	27	7	3
Income:	$37K	$28K	$0	$0
Status:	worker	worker	student	day care
Auto:			n/a	n/a

Stroud P et al. Spatial Dynamics of Pandemic Influenza in a Massive Artificial Society. *Journal of Artificial Societies and Social Simulation* 2007; 10(4):9.

The Locations

Home

Work

Home

Home

Home

Home

Shopping

School

Social

College

Passenger

Home

Home

Home

Stroud P et al. Spatial Dynamics of Pandemic Influenza in a Massive Artificial Society. *Journal of Artificial Societies and Social Simulation* 2007; 10(4):9.

A Typical Family's Day – Surveys

Carpool · **Work** · **Lunch** · **Work** · **Carpool**

Home · **Shopping** · **Home**

Car · **Daycare** · **Car**

Bus · **School** · **Bus**

time

Stroud P et al. Spatial Dynamics of Pandemic Influenza in a Massive Artificial Society. *Journal of Artificial Societies and Social Simulation* 2007; 10(4):9.

Others Use the Same Locations

Stroud P et al. Spatial Dynamics of Pandemic Influenza in a Massive Artificial Society. *Journal of Artificial Societies and Social Simulation* 2007; 10(4):9.
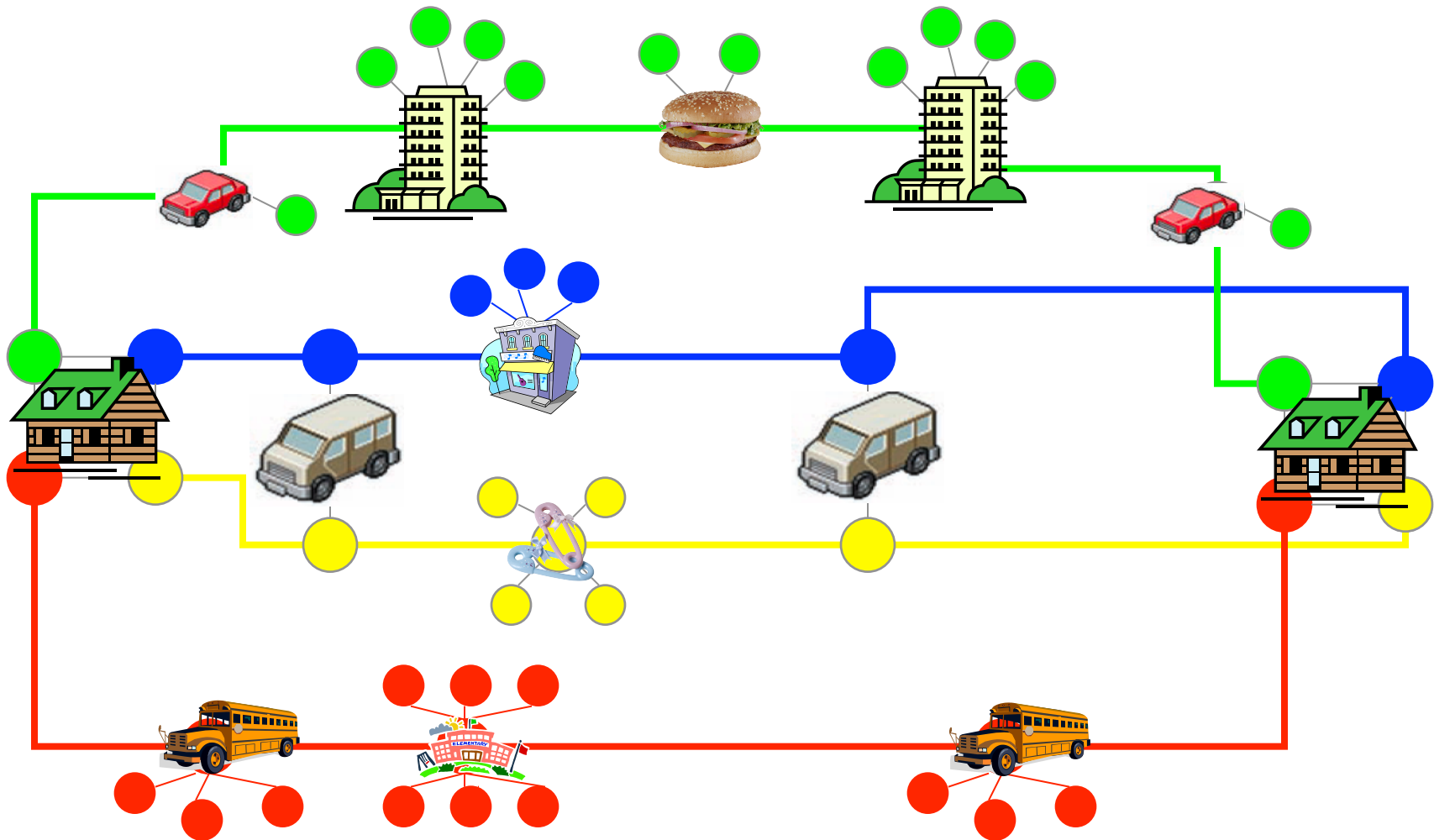
Bipartite Graph – Theory

People

Locations
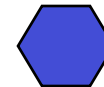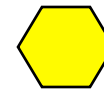
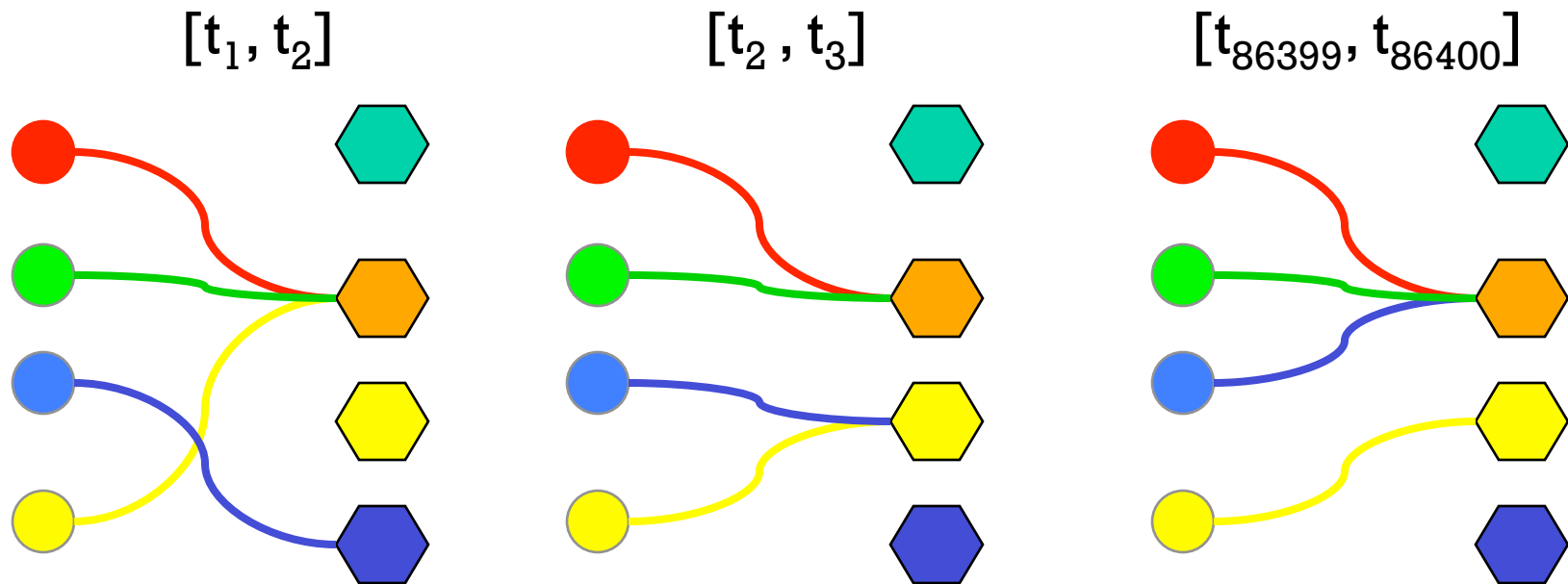# Bipartite Graph – Theory

Edge attributes:
- activity type: shop, work, school
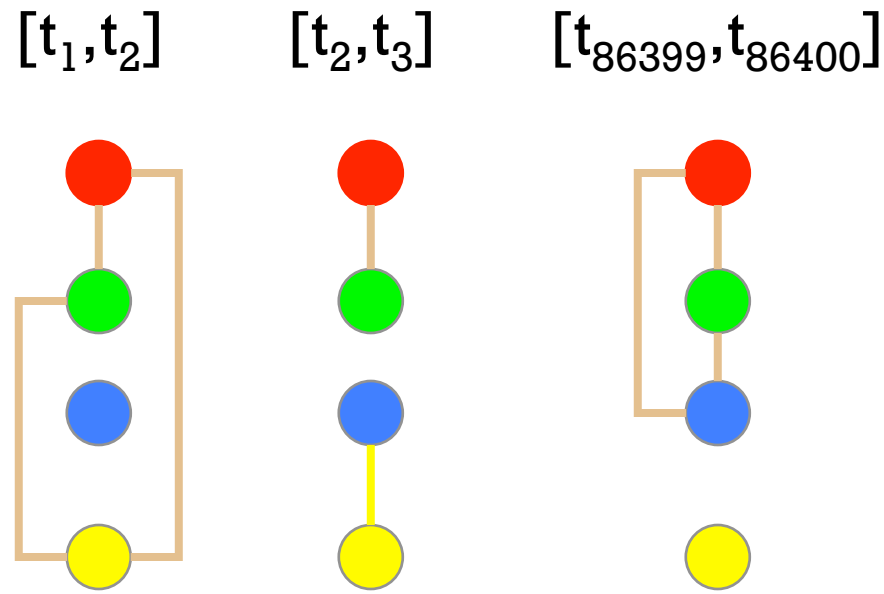- (start time 1, end time 1)
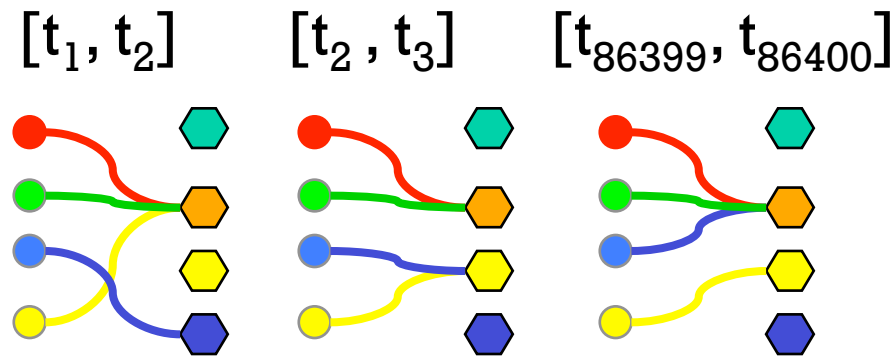- (start time 2, end time 2)
- …

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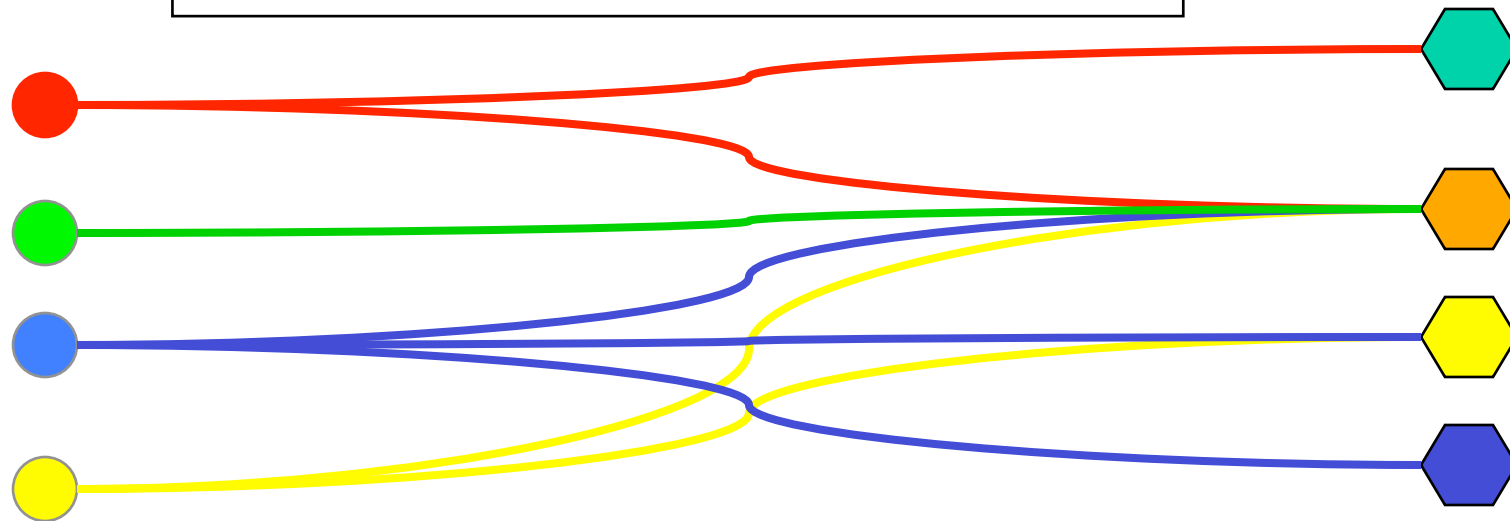
Explicitly Time Dependent – Theory
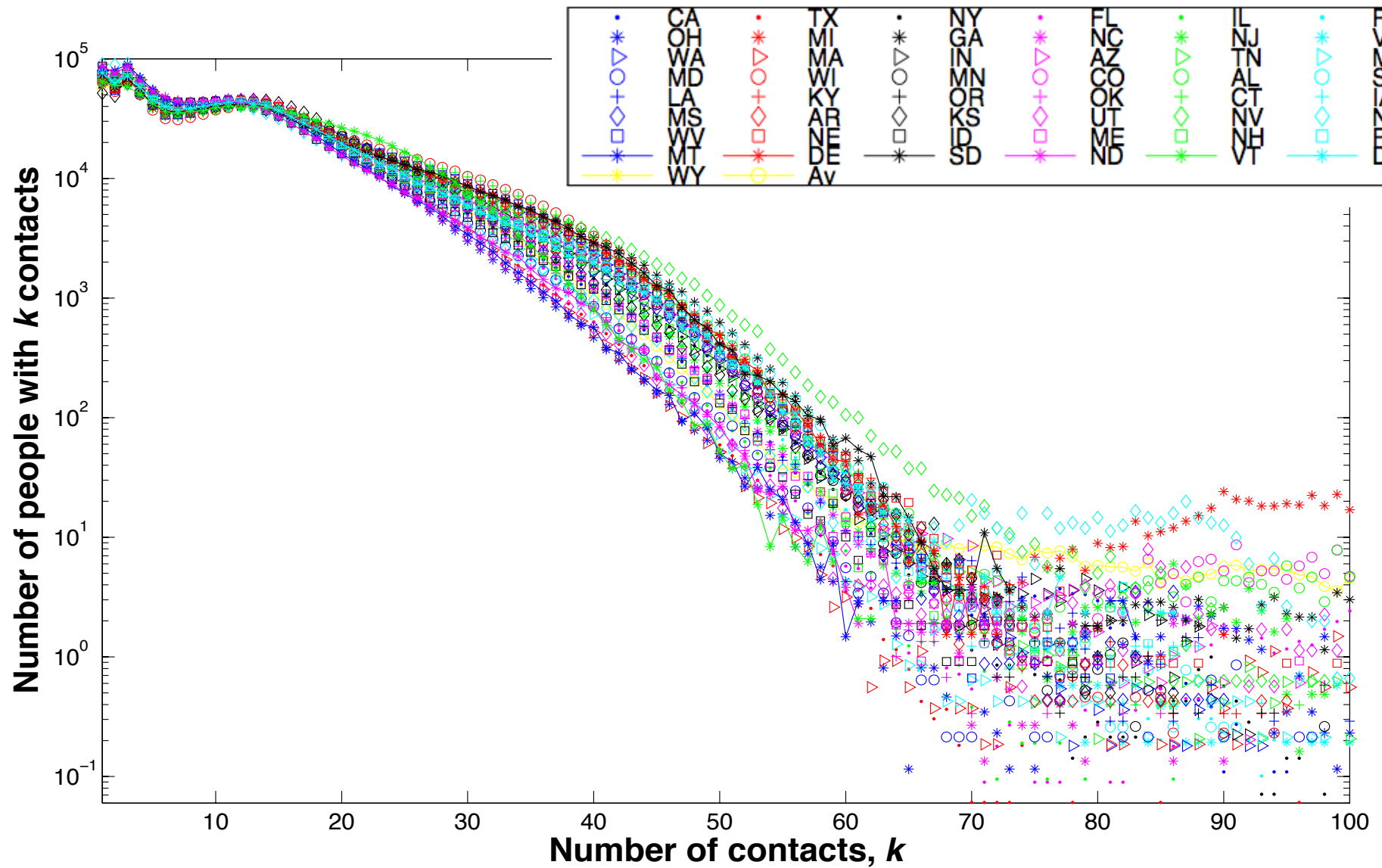
Edge attributes:
• activity type: home, work, school

$[t_1, t_2]$ $[t_2, t_3]$ $[t_{86399}, t_{86400}]$

People-people Graph – Theory

$[t_1, t_2]$ $[t_2, t_3]$ $[t_{86399}, t_{86400}]$

$[t_1, t_2]$ $[t_2, t_3]$ $[t_{86399}, t_{86400}]$

Social Contact Network Emerges

Degree
- 1 – 6
- 7 – 12
- 13 – 18
- 19 – 24
- 25 – 30
- 31 – 36
- 37+
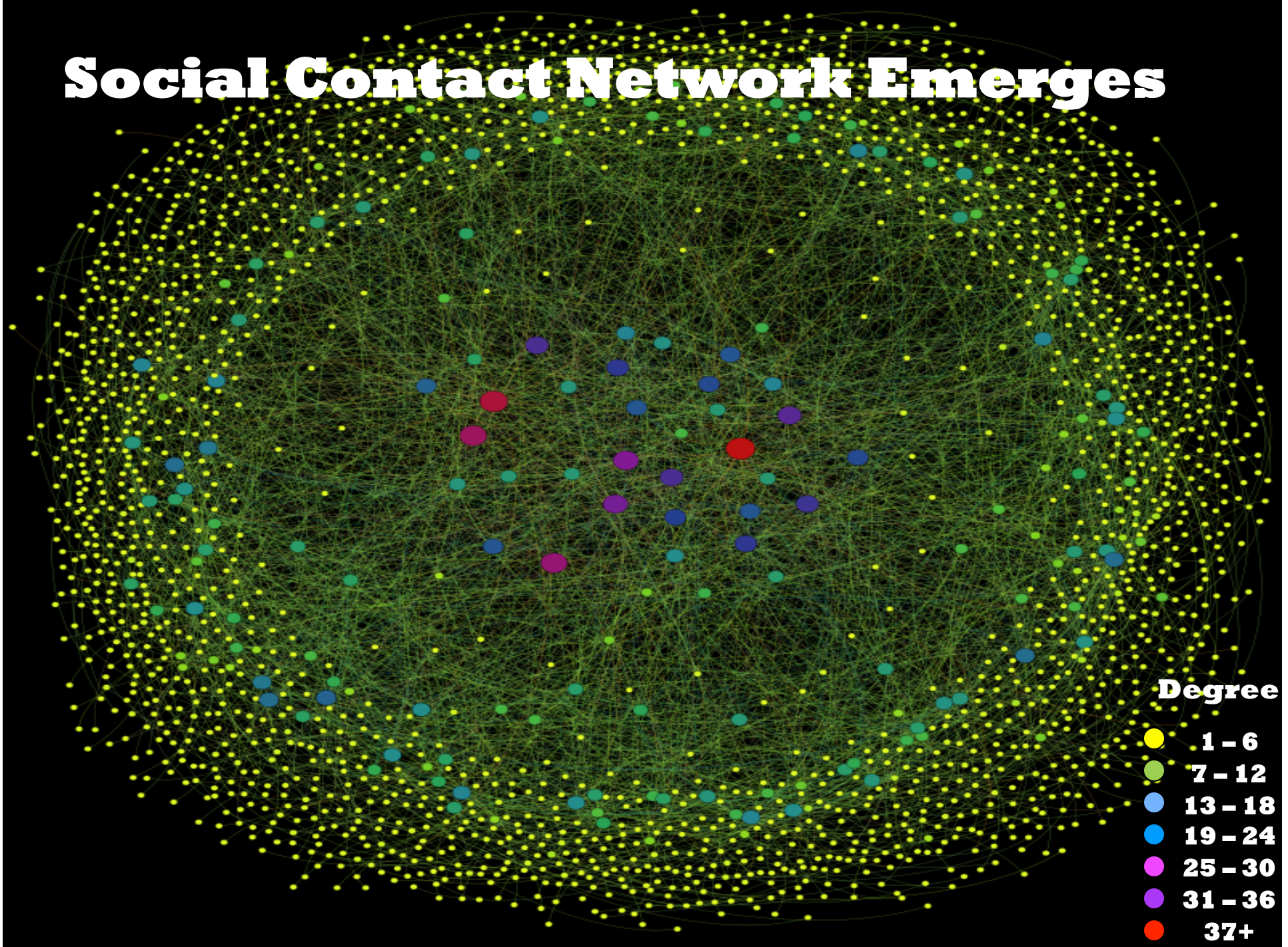
Degree Distribution

Del Valle et al. Estimating Mixing Patterns for the United States for Modeling Infectious Diseases (in preparation)

Demographic and Activity Differentiation
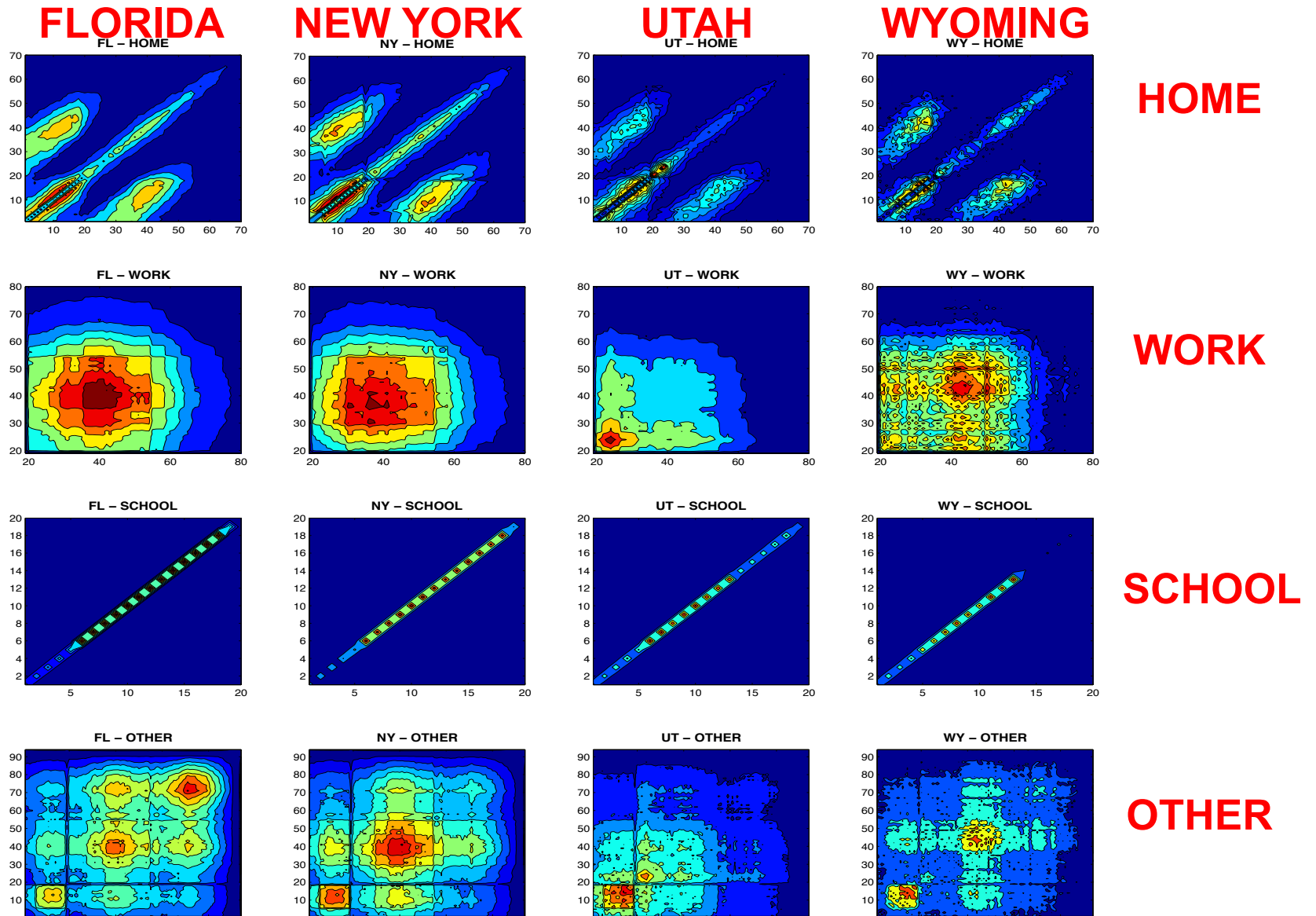
FLORIDA　　NEW YORK　　UTAH　　WYOMING

HOME

WORK

SCHOOL

OTHER

Del Valle et al. Estimating Mixing Patterns for the United States for Modeling Infectious Diseases (in preparation)
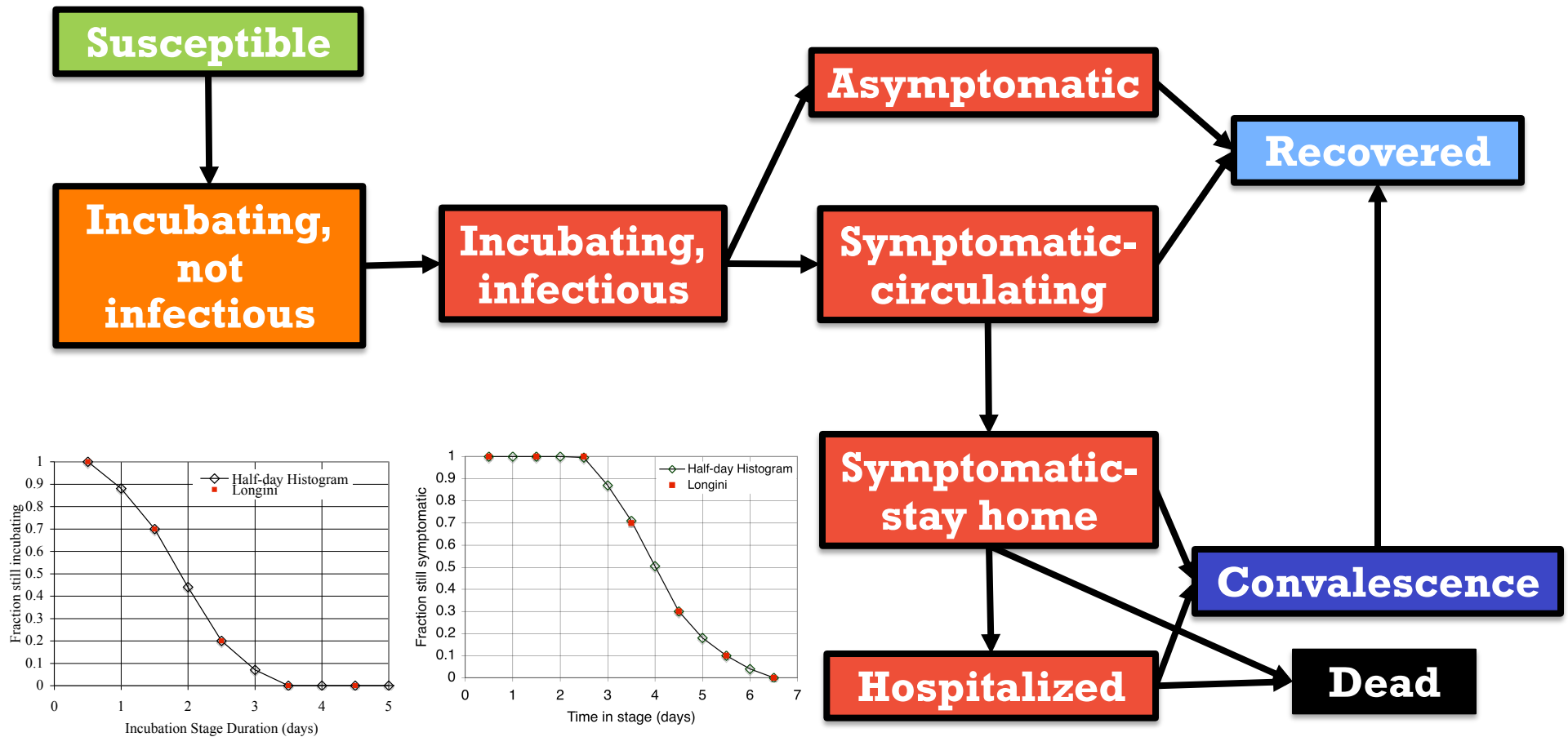
Population Age Distribution

Del Valle et al. Estimating Mixing Patterns for the United States for Modeling Infectious Diseases (in preparation)
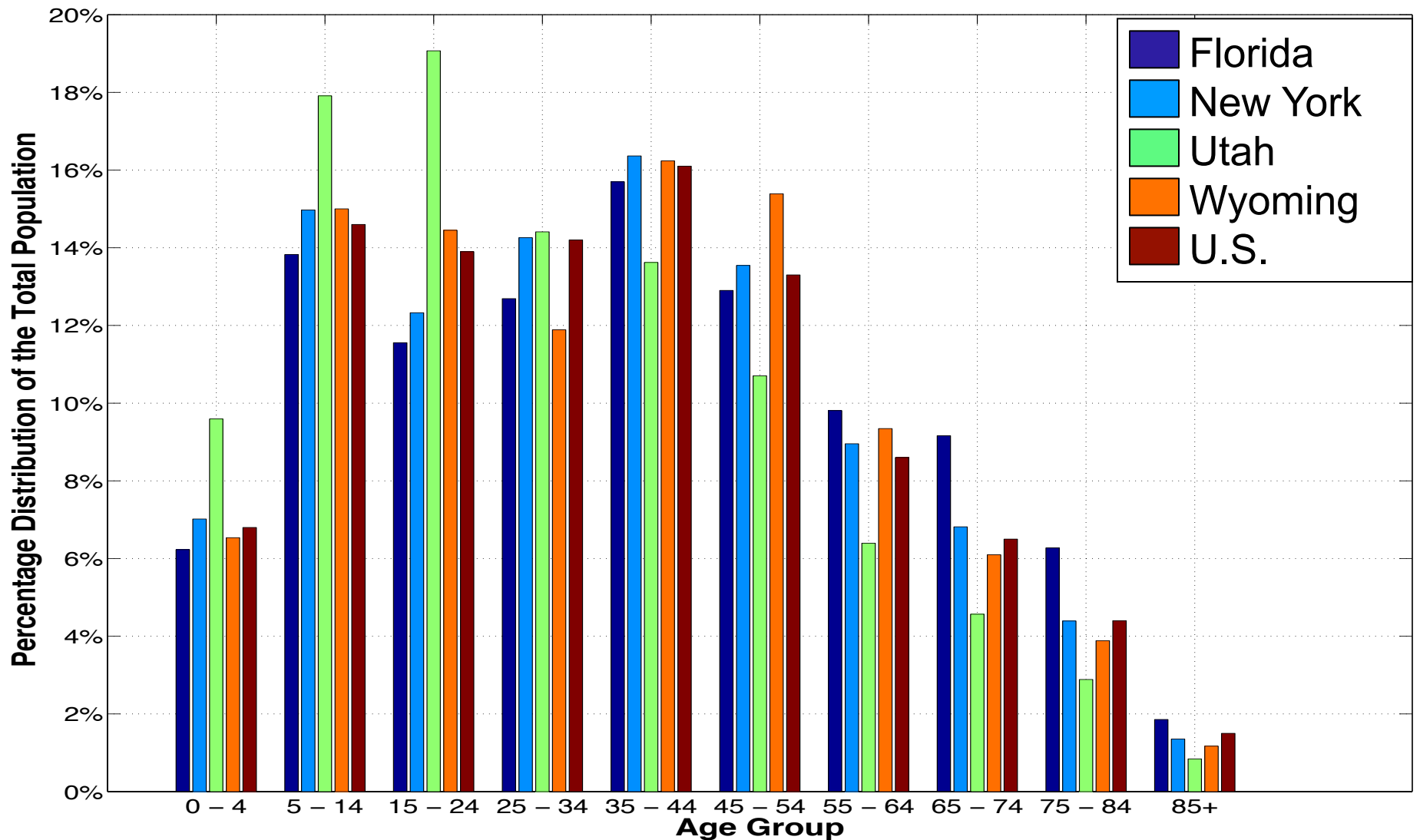
Comparison with Empirical Data
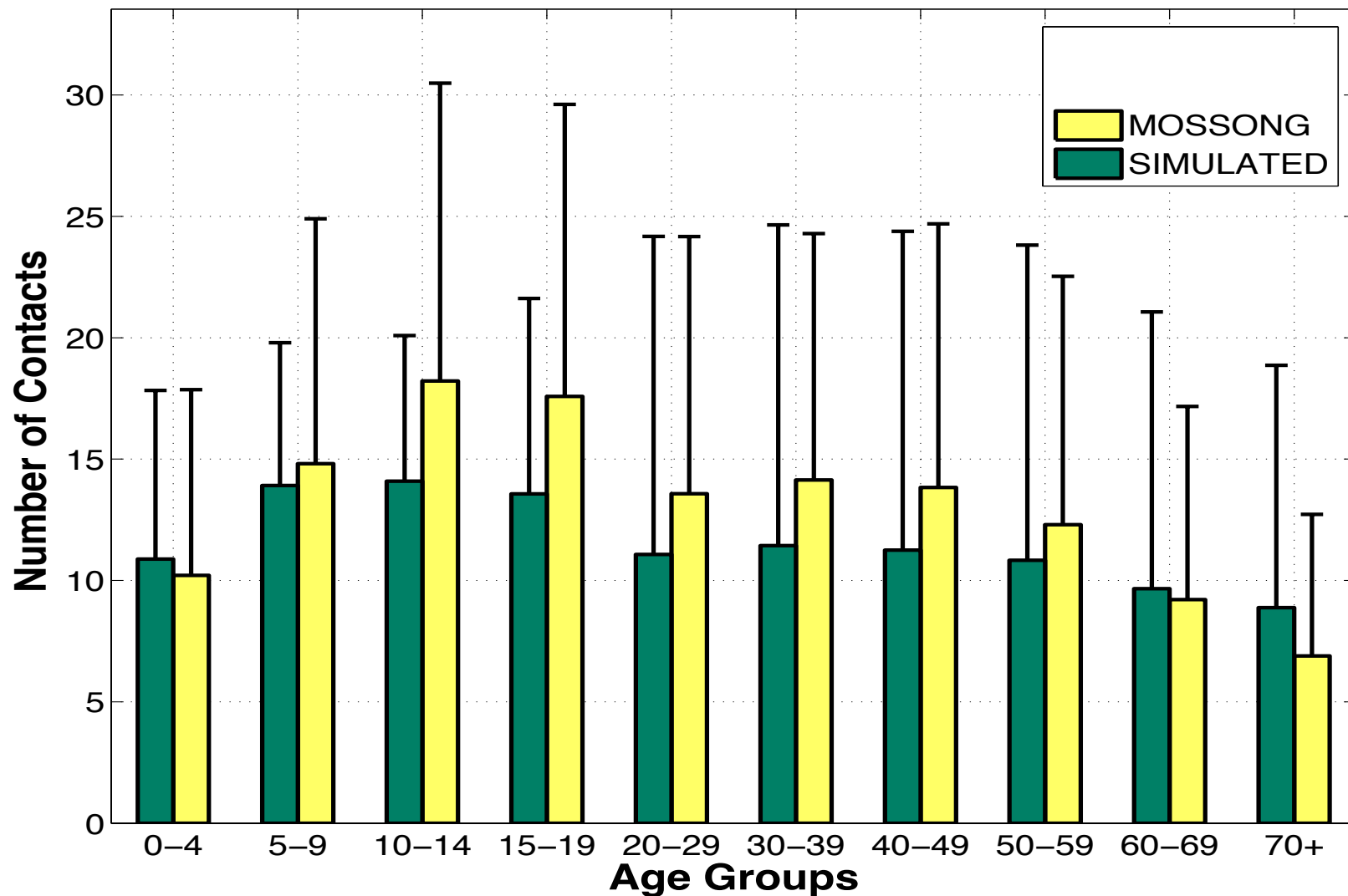
Mossong et al. Social Contacts and Mixing Patterns Relevant to the Spread of Infectious Diseases. **PLoS Med** 2008.

Disease Model in EpiSimS

Stroud P, Del Valle S, Sydoriak S, Riese J, Mniszewski S. Spatial Dynamics of Pandemic Influenza in a Massive Artificial Society. (2007) Journal of **Artificial Societies and Social Simulation**, 10(9).

Probability of Infection

$$P_j(t) = 1 - e^{-\sum_i TS_j I_i t_{ij}}$$

Susceptible Person j

All infected people co-located with j

Stroud P, Del Valle S, Sydoriak S, Riese J, Mniszewski S. Spatial Dynamics of Pandemic Influenza in a Massive Artificial Society. (2007) Journal of **Artificial Societies and Social Simulation**, 10(9).
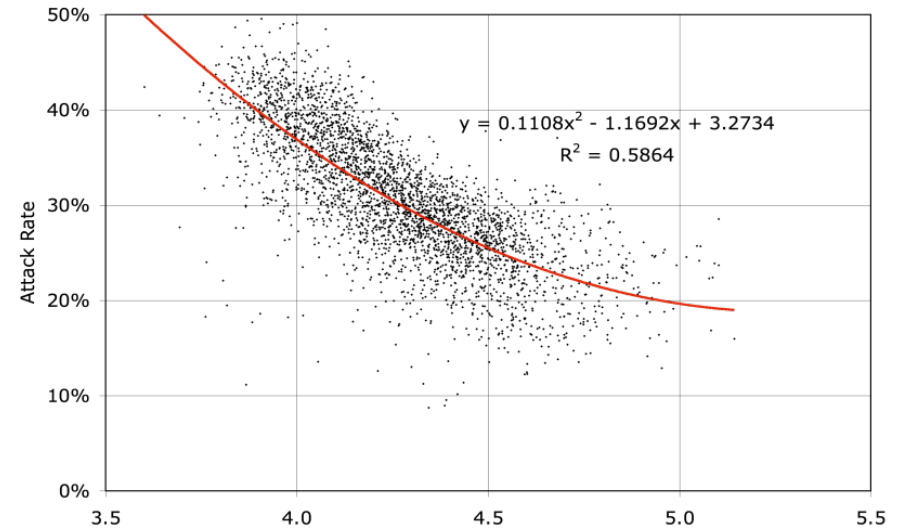
Attack rate
red: >35%
amber: 29% to 35%
grey: 17% to 29%
green: <17%

Stroud P et al. Spatial Dynamics of Pandemic Influenza in a Massive Artificial Society. *Journal of Artificial Societies and Social Simulation* 2007; 10(4):9.
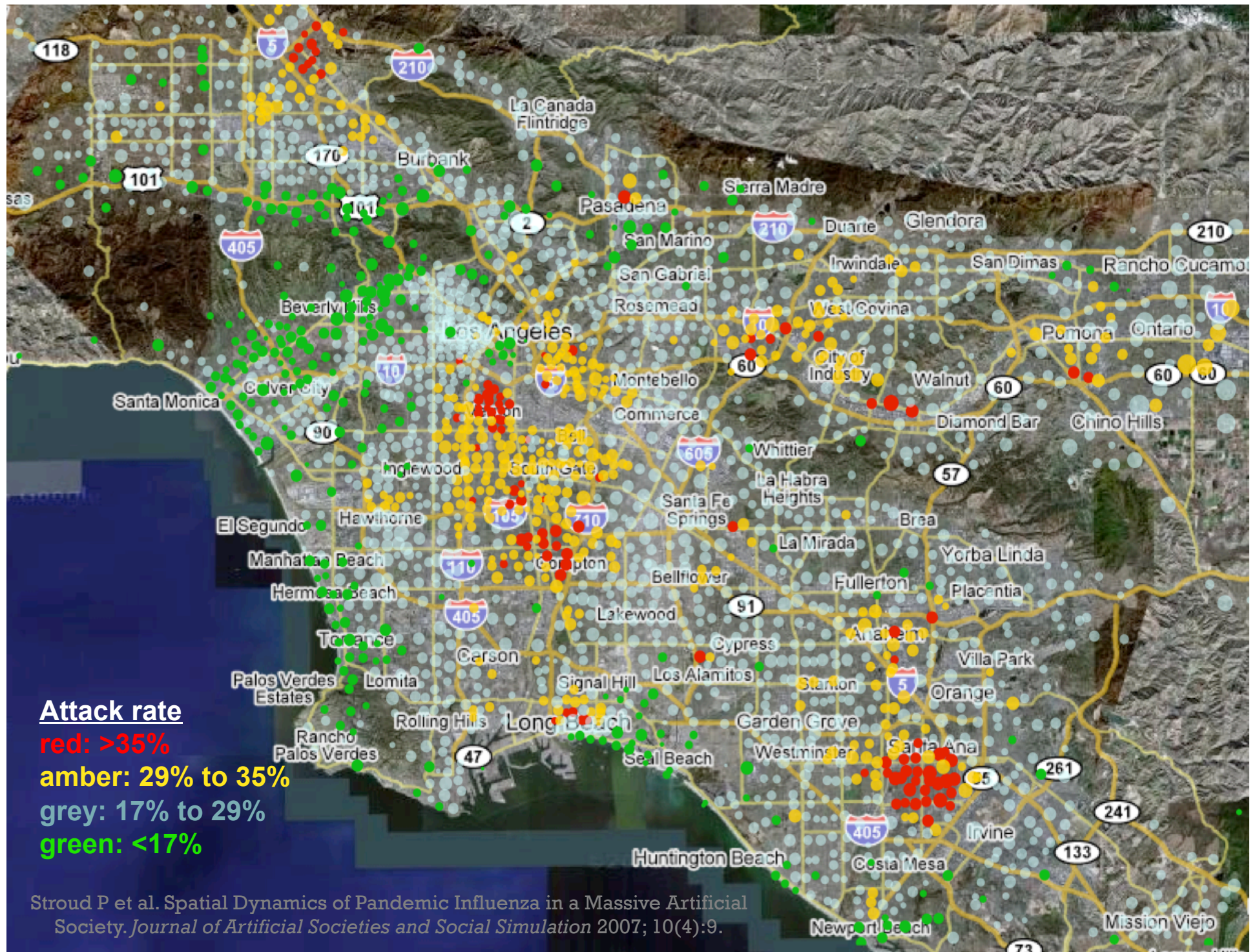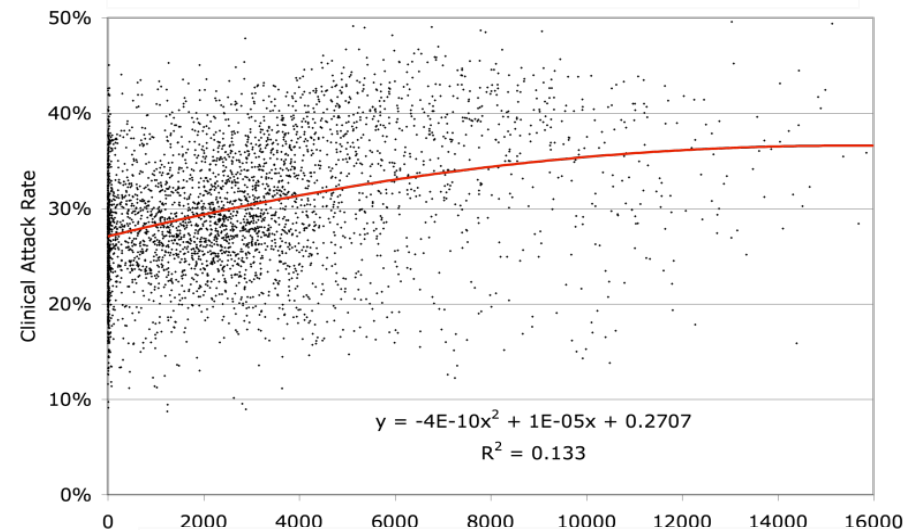
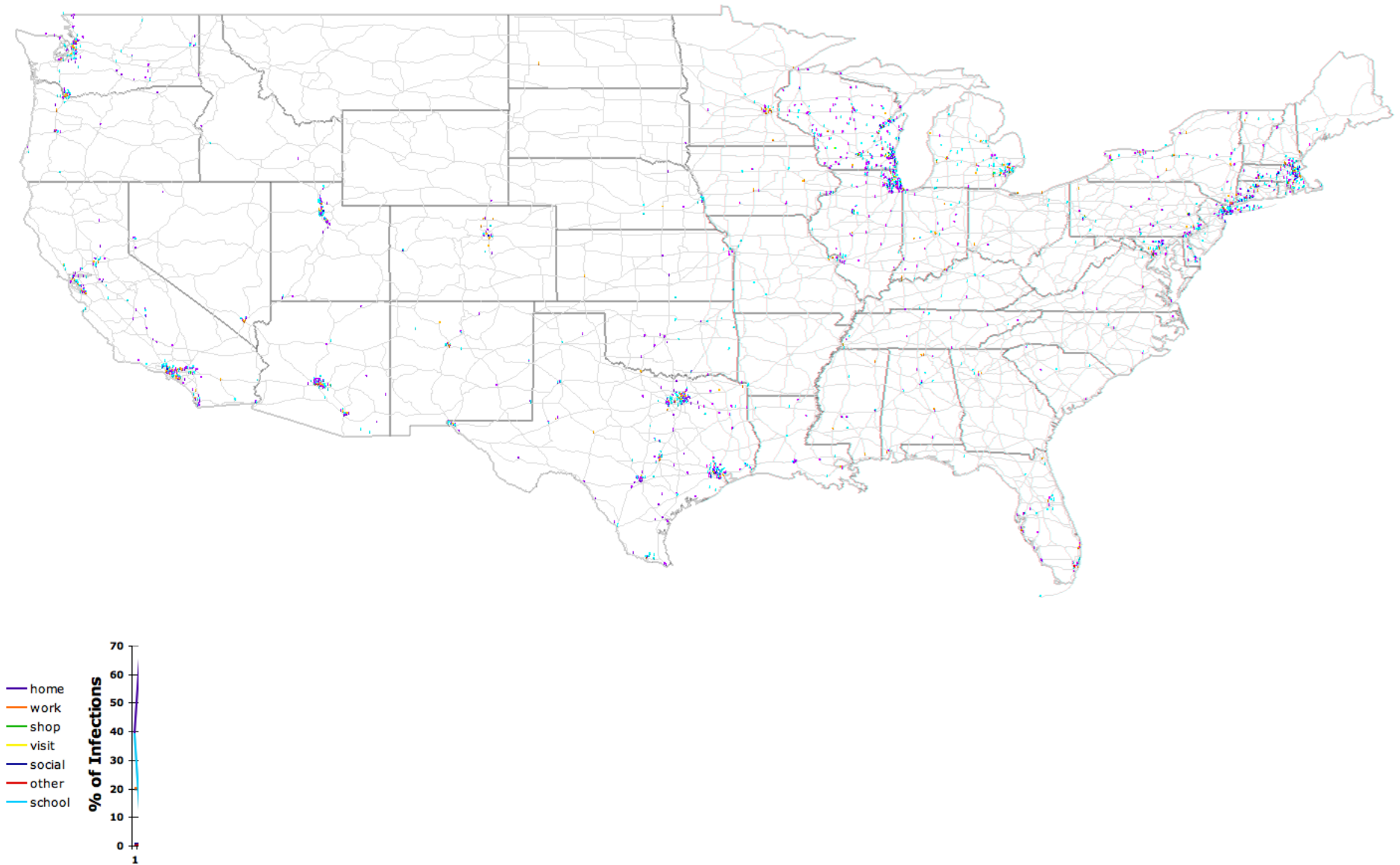# Attack Rate Correlates with Demographics
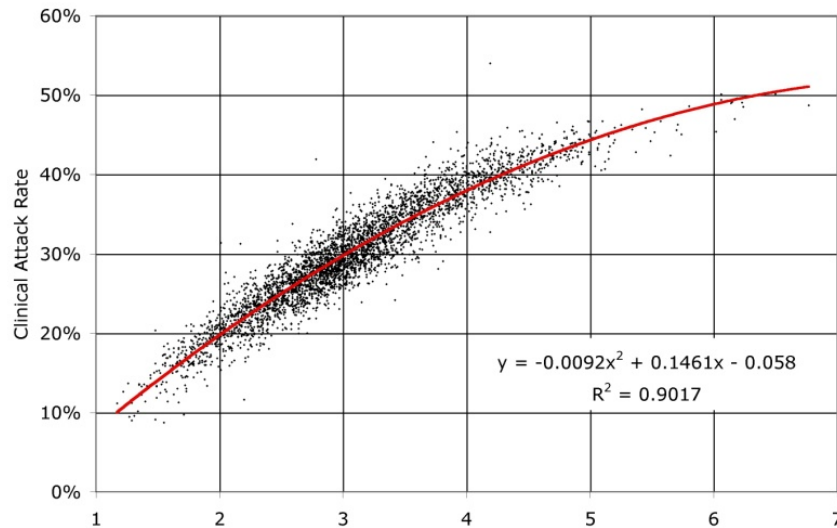
Average Household Size
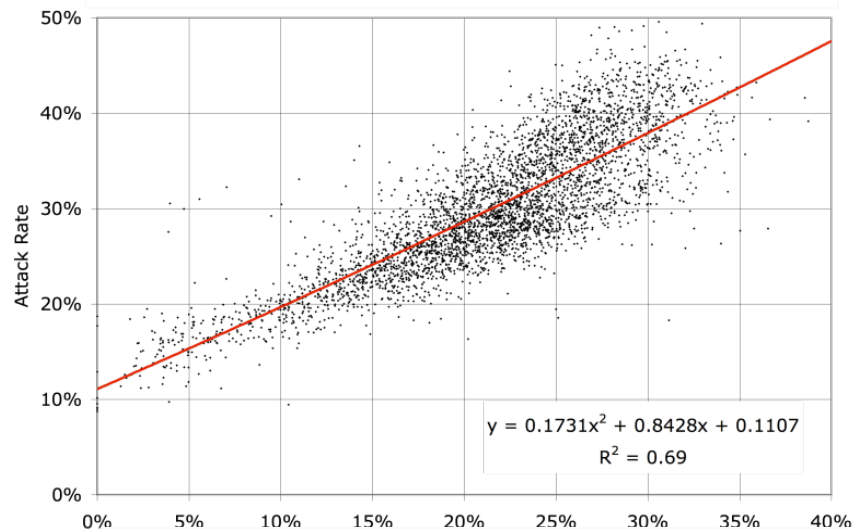
Per Capita Income
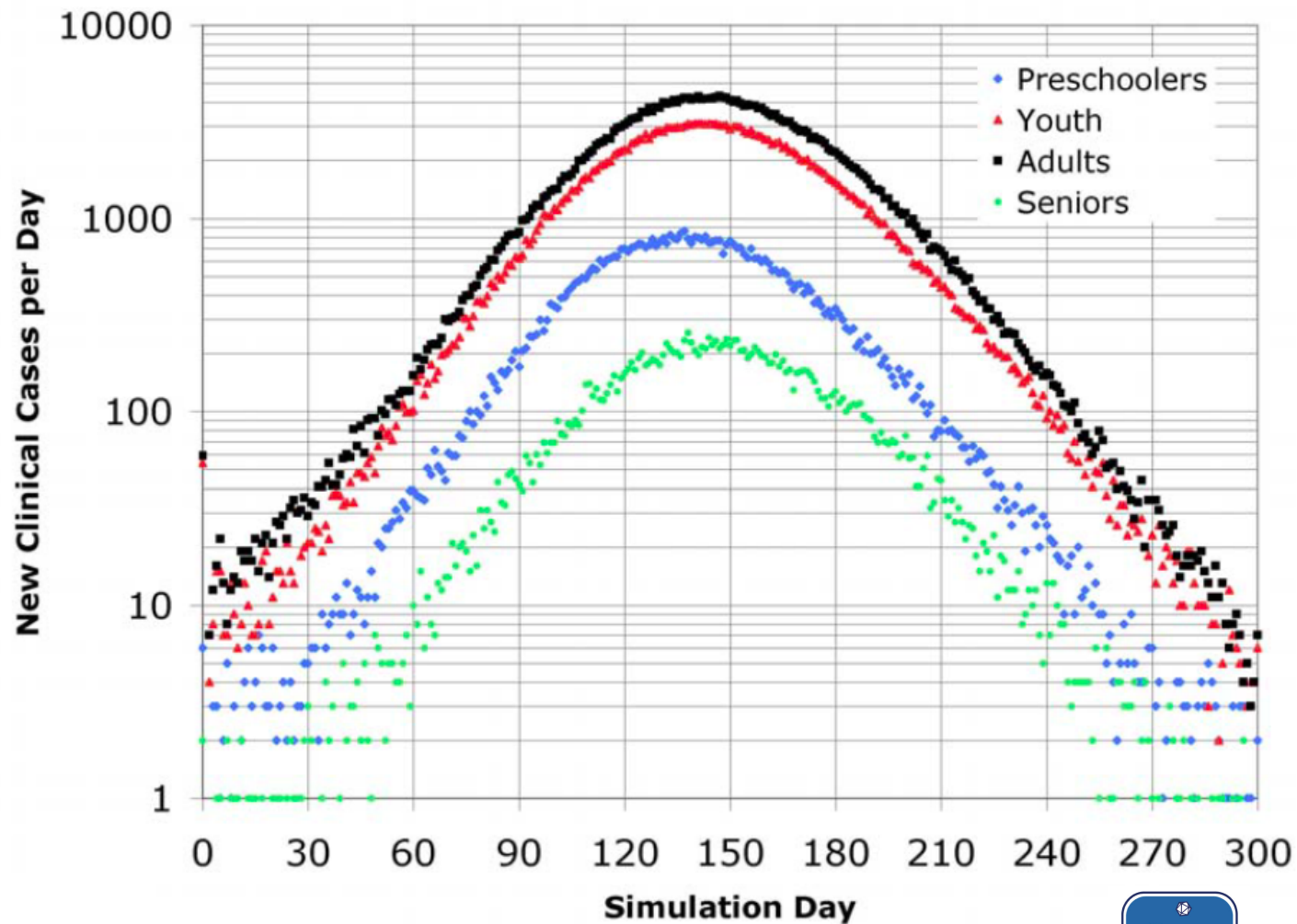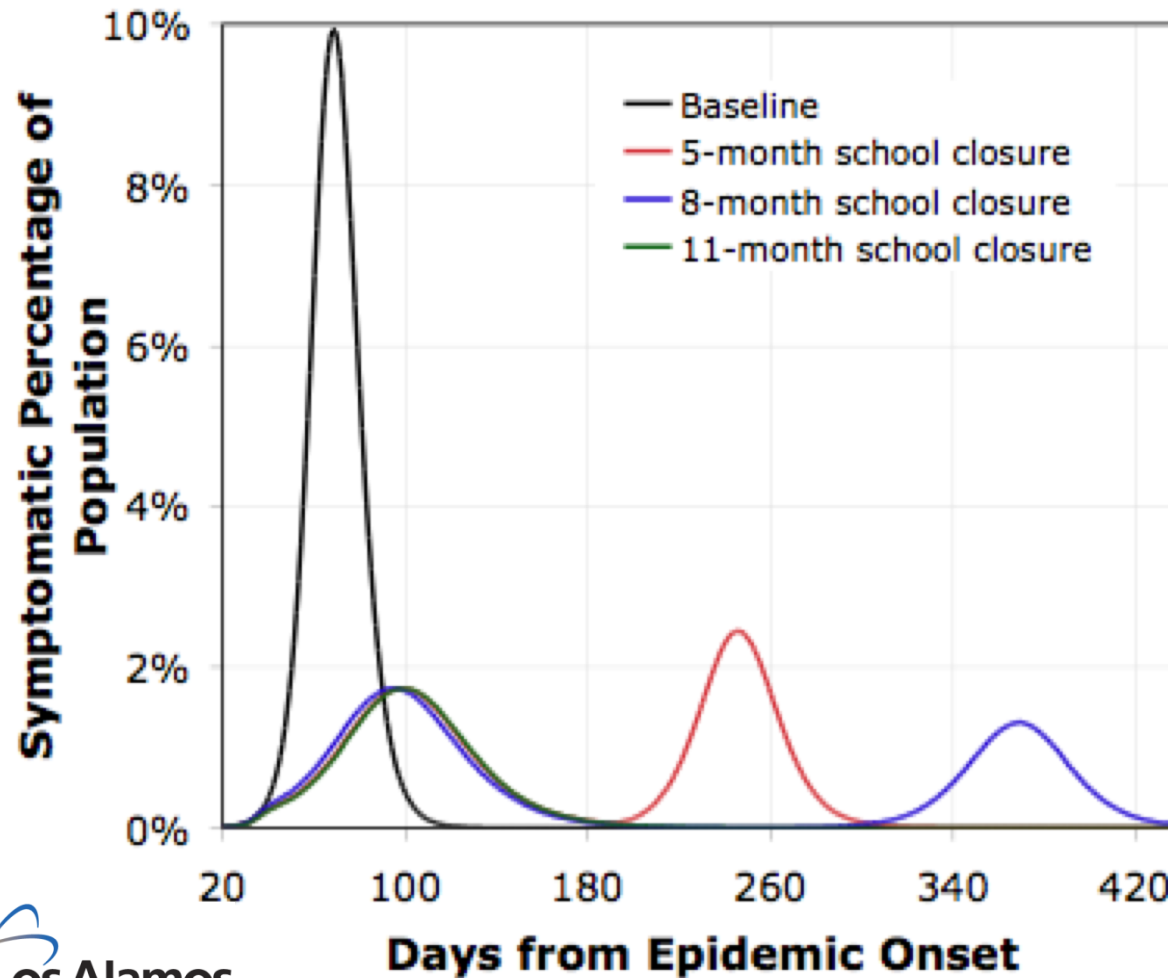
Population Aged 5 – 18

Population Density

Heterogeneous Spread
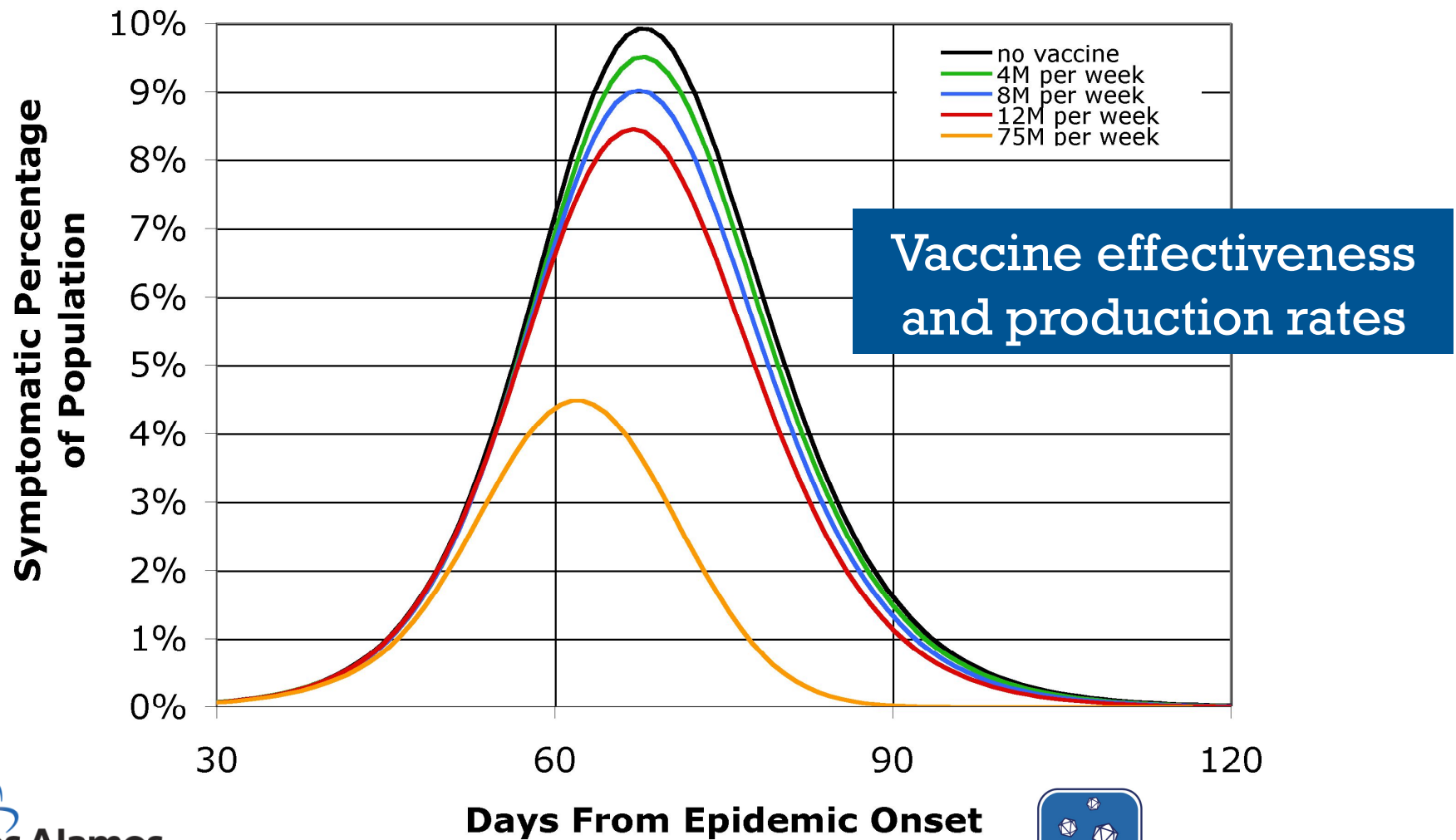
Demographic Differentiation

Impact of School Closures

Relaxing the closures can generate second wave of infection

Pharmaceutical Interventions
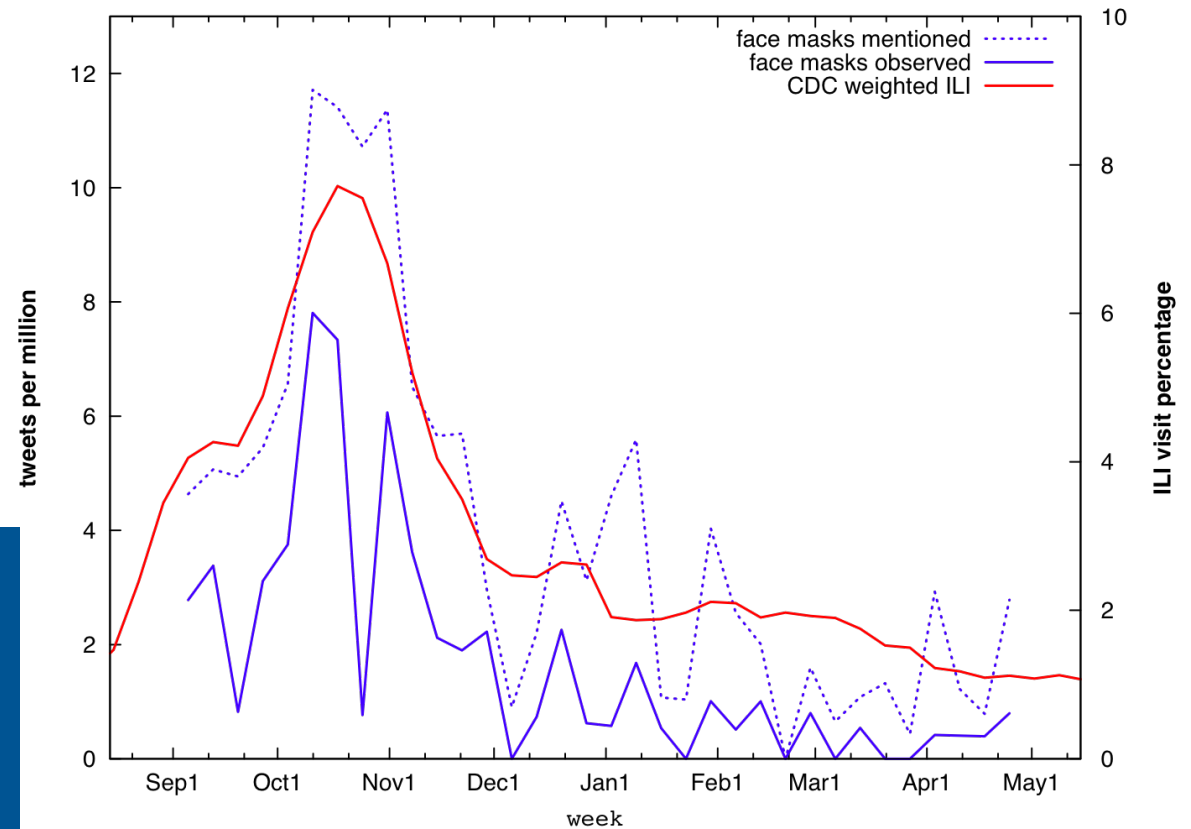
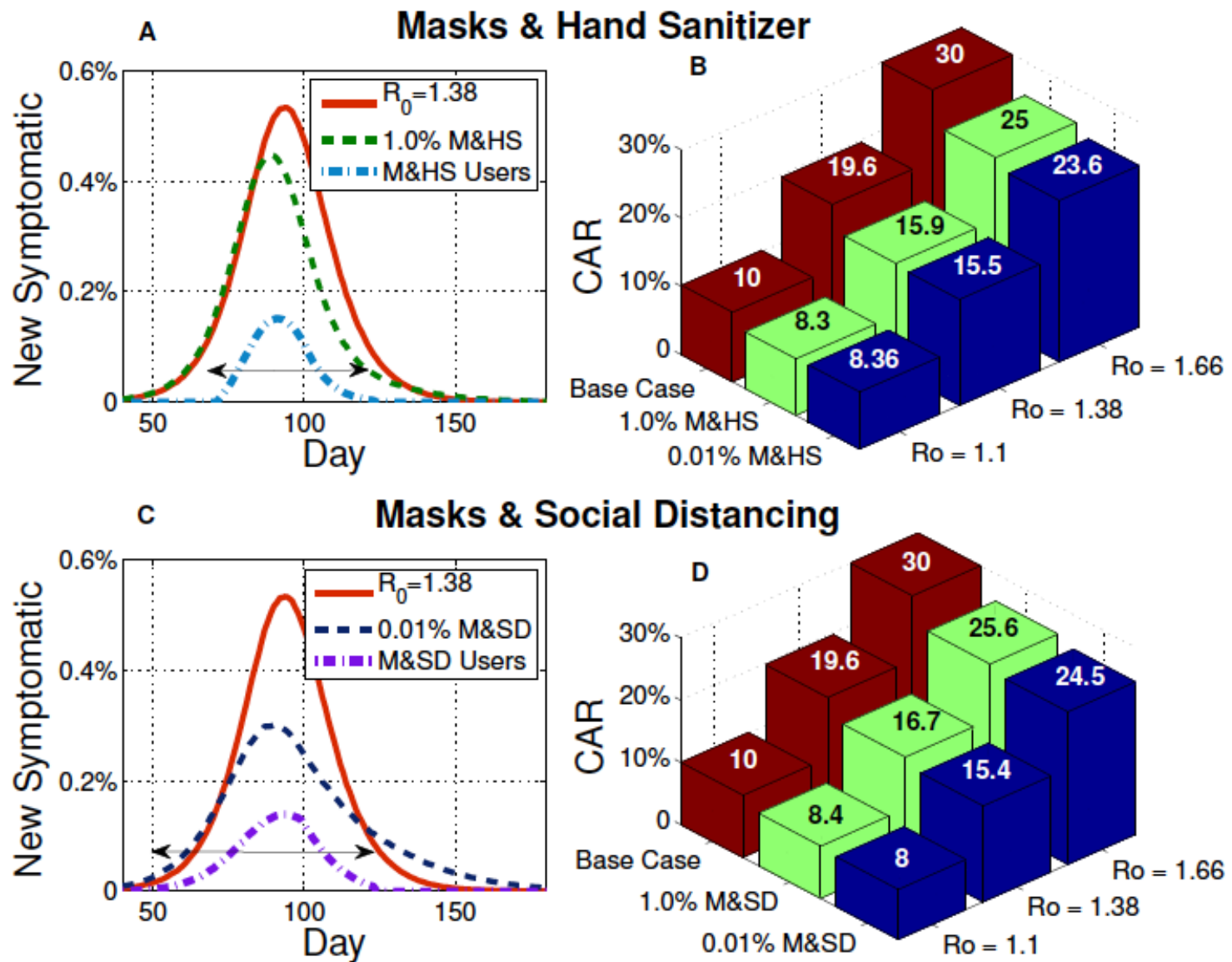# Social Media & Behavior

Demographic factors

Age

Gender

Ethnicity

Educational level

"Who" is likely to change behavior and "How" is implemented

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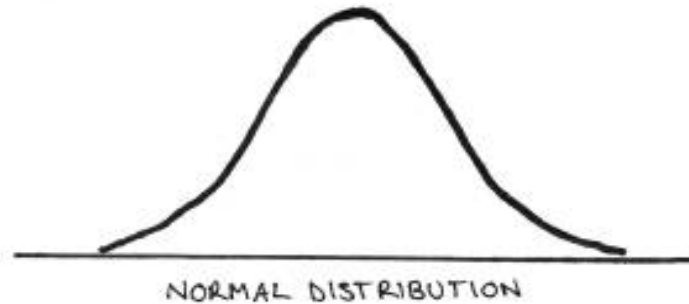
Facemask Study

Summary

- **ABMs provide a test-bed for:**

  - Testing hypothesis

  - Forecasting population demographics, infectious disease transmission, etc.

  - Developing complex social networks

Challenges and Opportunities

- Statistical Inference

- Model Fitting, Validation, and Verification

- Uncertainty Quantification for Agent-based Simulations

- Prediction & Forecasting

- Emulators

- Emergent Behavior

- Social Media

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Thank You!

J Epidemiol Community Health. 2006 January; 60(1): 6.– 7.